Thin Film ZnO Based Bulk Acoustic Mode Filters

C.W. Seabury, P.H. Kobrin, R. Addison,
Rockwell Science Center, Inc., Thousand Oaks CA 91358

D.P. Havens
Rockwell Filter Products, Costa Mesa, CA 92626

ABSTRACT

We have used thin film ZnO bulk mode resonators on an acoustically reflecting solid glass substrate to produce a variety of filters in the 1-3 GHz frequency bands. Power handling is large (>2W). Overall filter dimensions are very small (~1mm), while lithography requirements are undemanding (>10μm). A range of ladder filters has been produced with an average rejection to insertion loss ratio of ~ 10. Monolithic inductors have also been used to improve characteristics over specified bands.

INTRODUCTION

RF filters in the 1-3GHz frequency bands, based on thin film, bulk mode resonators have been investigated for some time [1,2]. They are considerably smaller than ceramic filters, and offer higher potential performance than SAW devices. The early designs used free-standing membranes, produced by a backside via process, to acoustically isolate the resonator from the substrate. Two problems have plagued this approach. First, the backside via holes make wafer handling and die packaging very difficult. Second, the intrinsic compressive stress of the sputtered piezoelectric films produces distortion, and thus poor reproducibility and yield. Surface micromachined air-bridge designs make wafer handling easier, but are just as sensitive to film stress.[3,4]

A more recent approach has involved a solid substrate with the acoustic equivalent of a Bragg reflector grown on top, for isolation [5, 6, 7]. Figure 1 shows a schematic cross section of such a resonator. Proper choice of the reflective materials and deposition process, can produce very high reflectivity over a wide bandwidth. Figure 2 shows the calculated reflectivity for a 1/2 wave resonator such as that in Fig. 1. The small, narrow dip at F/Fo=1 is the resonance itself. It can be seen that the reflectivity bandwidth of the reflector is much greater than the width of the resonance itself. Therefore resonators with many different frequencies can be fabricated on the same substrate. This feature allows the convenient monolithic integration of multipole filters.

The solid substrate also eliminates the stress induced film distortion, giving much more consistent results, while offering the potential for low cost, through conventional batch processing and simpler packaging.

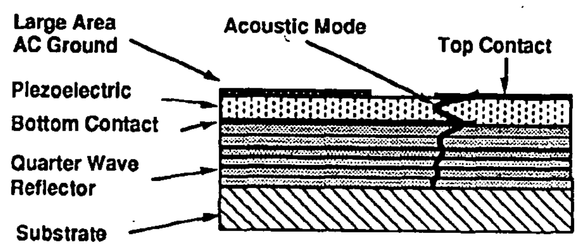

Fig. 1 Cross section of a completed resonator. The solid curve represents the strain field of the acoustic mode. The substrate may be virtually any insulating material.

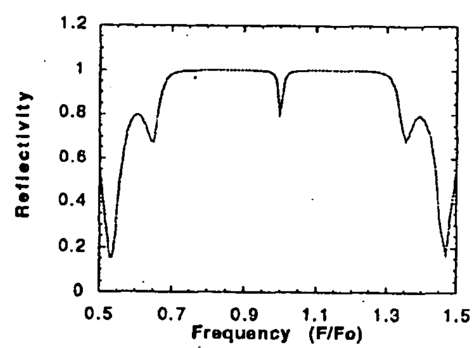

Fig. 2 Calculated reflectivity for a 1/2 wave resonator at Fo, fabricated on a Bragg reflector consisting of multiple pairs of dielectric layers of different acoustic impedance, each 1/4 wave thick.

PROCESS

We have fabricated our substrates (glass, semi-insulating GaAs, and high resistivity Si have been used) by vacuum depositing several pairs of 1/4 wavelength layers, consisting of high and a low acoustic impedance dielectric materials. Lower electrodes are then deposited and patterned using standard techniques.

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The 1–2 µm thick ZnO film is deposited by reactive RF magnetron sputtering at elevated temperature. Typical X ray rocking curve FWHM are ~4.5°. Interestingly we have seen little correlation between the X ray FWHM and the resonator properties for values below ~6°. Resistivity is greater than 10^7 ohm cm.

A second level metal is deposited directly on top of the ZnO and patterned. Large area, capacitively coupled AC connection to the bottom contact is used to avoid the need for vias through the piezoelectric.

At this point discrete resonators and other test devices can be probed, to measure the center frequency and the pole-zero spacing. Multipole ladder filters, require that the pole of the shunt resonator aligns with the zero of the series resonator. Therefore, a thin load dielectric is deposited selectively over the shunt resonators to shift the frequency by precisely this amount. A final global trimming layer may then be added, to adjust the center frequency of the filters as well as provide passivation.

RESONATOR CHARACTERISTICS

To evaluate the quality of the Bragg reflector, we fabricated discrete resonators using both the reflecting substrate and our previous air-bridge design, depositing the ZnO piezoelectric on both simultaneously. The comparison is shown in Fig. 3. The values of "Q" are nearly identical at ~300.

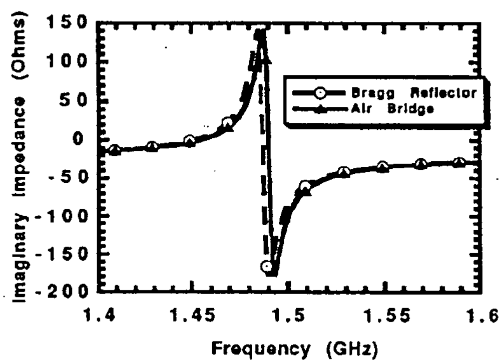

Fig. 3 Imaginary impedance spectra for discrete ZnO resonators. K_{cm} =0.22 for the Bragg reflector device and K_{em}= 0.23 for the air-bridge. Q=300 for both devices.

These results indicate that the reflector contributes little or no loss to the resonator. The "Q" is nearly entirely limited by acoustic losses in the piezoelectric material itself. The calculated intrinsic loss from the finite reflectivity of the reflector alone would yield a Q > 2000.

To avoid the ambiguities of deconvoluting single resonator data, ladder structures were used to measure the pole zero spacing. If the series and shunt elements are identical, then there will be two attenuation maxima, corresponding to the impedance pole of the series resonator and the zero of the shunt resonator. Figure 4 shows the data for an unshifted 3 pole filter on a Bragg substrate. The separation between the two dips, is 46 MHz indicating a K_{eff} of 0.22. The air bridge devices gave very similar results. One-dimensional acoustic modeling indicates that, in the case of the Bragg reflector, the penetration of the mechanical energy into the reflector accounts for much of the difference between the measured effective resonator value, and the bulk material value. Likewise, the air-bridge device has a thick SiNx support membrane which is included in the resonant structure. Assuming a bulk material coupling for ZnO of K=0.28, the calculated effective resonator coupling on the composite structures is K= 0.24. Our measured value of 0.22 implies that the thin film material is very close to bulk-like in its piezoelectric coupling.

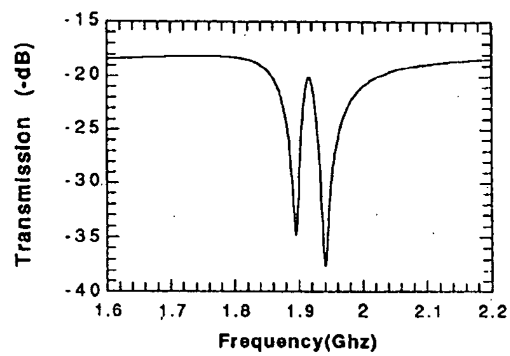

Fig. 4 Transmission characteristics of an untuned 3 pole ladder structure on a Bragg reflector substrate.

TEMPERATURE COMPENSATION

In ZnO has a bulk temperature coefficient of acoustic velocity change of -60ppm/°C. However SiO_2 has a coefficient of +80ppm/°C. By adding a symmetric cladding of SiO_2 on the top and bottom of the resonator, and reducing the thickness of the ZnO, the net temperature drift of the resonance frequency can be compensated, while maintaining the same center frequency. [8] Because the added material is at the edges of the acoustic mode, as shown in Fig. 5a, the overlap integral of the electric field and the acoustic mode in the ZnO is not actually reduced significantly. Thus we see little or no change in the coupling constant or the Q of the resonators. Figure 5 b shows the effect of the added material on the total K_{em} of the composite structure as a function of the ratio of ZnO to the total resonator length. This model calculation does not include the effect of the contact metals or the Bragg reflector. Also there is little data on the temperature coefficient of velocity for thin films.

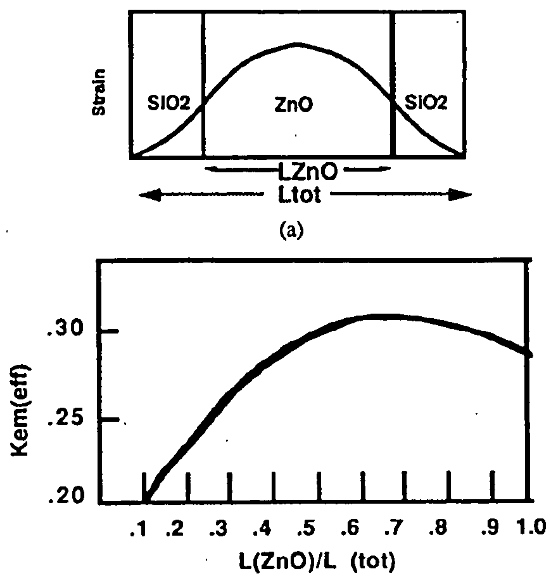

Fig. 5 a) Schematic of the overlap of the acoustic mode with a 3 layer composite resonator. b) Calculated effective Kem of the composite resonator as a function of the ratio of ZnO to the total cavity length.

Figure 6 shows actual data from measured resonators. The bottom curve is for an uncompensated ZnO resonator. The middle is for a similar resonator but which included an extra 3000Å layer of SiO_2 in the substrate structure. The top curve is for a completely symmetrically cladded resonator with SiO_2 on both the top and bottom. The net drift for this device is ~10ppm/°C. In principal one should be able to completely cancel the first order coefficient of temperature drift. K_{∞} for the compensated device was 0.22.

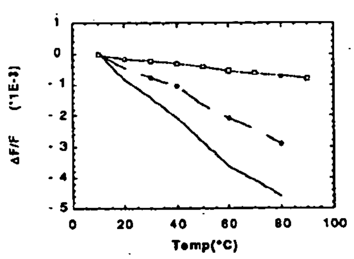

Fig. 6 Resonance shift characteristics of 3 different structures. Solid curve is an uncompensated ZnO resonator. The middle dashed curve is the same design, but with an addi-tional 3000Å SiO_2 layer below the ZnO resonator. The top curve is the same device after an additional 3000Å of SiO_2 was deposited on top. ZnO thickness was 8000Å.

FILTERS

A variety of filter designs have been fabricated in this technology, ranging from 2 to 5 poles. For a conventional ladder design, the ratio between rejection and minimum insertion loss, is determined by the figure of merit of the resonators (K_2 *Q). Our material has ranged from a value of 15 to 20. The typical rejection to insertion loss ratio which results is ~10. Figure 7. shows a set of curves for three different designs. The bottom curve is a 30 MHz wide 5 pole filter with 44dB rejection and ~4.5dB insertion loss. The middle curve is a 44MHz wide 5 pole with 27 dB rejection and 2.8dB insertion loss. The top curve is a 30 MHz wide 3 pole filter with 23dB rejection and ~2.2dB insertion loss.

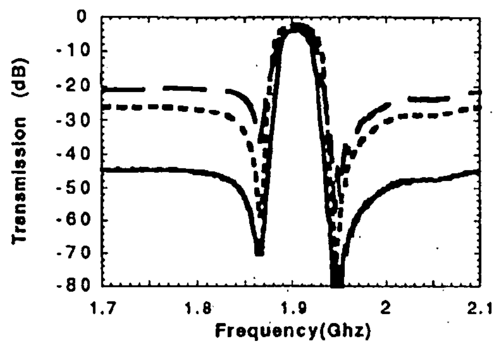

Fig. 7 Transmission spectra for several ladder filter designs. Solid Curve is a 5 pole 30 MHz B.W. design. Dotted curve is a 5 pole 44 MHz design. Dashed curve is a 3 pole 30 MHz Design.

INDUCTIVE COMPENSATION

The out-of-band rejection of a ladder filter depends on the ratio of the residual capacitance of the series and shunt elements (C_0). One can therefore modify the filter characteristics by incorporating inductors, to compensate for the residual reactive admittance of the series path, and the reactive impedance of the shunt resonator. The rejection can, for example, be increased in the compensated region at the expense of less rejection far from the band center, without increasing the in-band loss.

Because these filters are fabricated on an insulating substrate, high Q monolithic inductors and capacitors can be naturally integrated. Figure 8 shows the layout of a two pole filter designed for 50 ohm matching, with one spiral inductor in parallel with the series resonator and one in series with the shunt resonator. Note that the series resonator is implemented in two stages to avoid the need to contact the bottom electrode. Even with the inductors, the overall die dimensions are ~1mmx1mm. Figure 9 shows the transmission characteristics of the inductively compensated filter as well as the same 2 pole design without the inductors. Minimum insertion loss of both designs is ~1.6dB. The Q of the large inductor, measured on separate test devices was only ~7 using 4 micron thick Al for metalization. Thicker metal should improve this value and would result in even higher near in rejection.

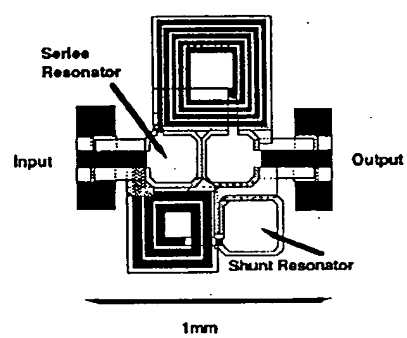

Fig. 8. Layout of a two pole filter with monolithic compensating inductors on both series and shunt arms.

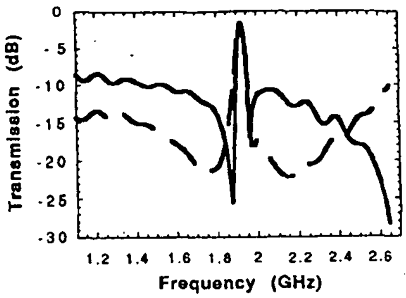

Fig. 9 Transmission spectra for a 2 pole ladder filter. Solid curve is for the 2 pole itself. Dashed curve is for a 2 pole with monolithic inductors on both series and shunt arms.

CONCLUSION

Thin film ZnO piezoelectric combined with an acoustic Bragg reflector substrate has been used to produce a range of filters between 1 and 2 GHz. The solid substrate does not result in any significant performance penalty. It also allows low cost conventional semiconductor batch processing to be used. The process includes the steps necessary for fabricating passive inductors and capacitors, making integration of impedance matching elements straight forward. Temperature compensated designs have been demonstrated.

Because the frequency is determined by layer thickness rather than fine line lithography, the approach can be used at frequencies up to 5-6 GHz without substantial modification. Performance is comparable to existing technologies, and appears limited by piezoelectric material quality, not by the reflector design. Improvements in the deposition technology should make this an attractive alternative to current ceramic and saw technologies for many wireless applications.

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Sci. Center, Rockwell Int. Corp., Thousand Oaks, CA;

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Index Terms:
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